N S G - 57-60

17 p

Shock Deformation of Quartz from Two Meteorite Craters

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double-code
1516681
1860212

(NASA CR-53681)
N65-83212
Code None

[1964] 17 p refs

UNPUBLISHED PRELIMINARY DATA

Abstract

Quartz, in association with coesite and silica glass from two meteorite impact sites, Meteor Crater, Arizona, and Wabar Craters, Saudi Arabia, commonly exhibits prominent cleavage and gross deformation. These features are unlike those that occur in quartz from regions deformed by other geologic processes.

Cleavage in quartz specimens was probably induced by brittle fracturing under shock loading and is similar to ruptures developed in quartz by static loading and shock loading experiments.

Introduction

During a petrographic investigation of rock materials from meteorite craters it was found that quartz displayed certain textures distinct from quartz of other geologic environments. Quartz in association with coesite and silica glass from two meteorite craters, Meteor Crater, Arizona, and Wabar Crater, Saudi Arabia, shows well-developed cleavage. Milton, and others (1962) described regular fractures, that were termed either parting or cleavage, in deformed rocks from the Scooter high-explosive cratering experiment. Englund and Roen (1962) reported intensely deformed quartz that displayed parallel fracture patterns from the Middlesboro Basin, Kentucky, cryptoexplosion

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(NASA Grant NsG-57-60, suppl. 1-62; NASA Grant NsG-593) RC#2

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structure. This discussion illustrates the extensive development of cleavage in quartz.

It is difficult to find a widely accepted usage of the terms fracture, cleavage, and parting. In describing breaks in a solid body that has been under an unknown stress system (i.e., deformation by natural processes, not by experimental devices), it is of particular interest to determine if these breaks are controlled by the crystal structure or if they occur randomly. In a geological sense, the three above terms can be used to describe a break in a mineral that has undergone stress.

The following is an account of the way these terms will be used in this paper. Fracture is the separation or fragmentation of a solid body into two or more parts under the action of stress. If fracture occurs with appreciable plastic deformation prior to and during the propagation of a crack, it is a ductile fracture. If the fracture is characterized by lack of gross plastic deformation, it is termed a brittle fracture. These terms describe a break in a solid body as the result of stress, but they are not completely satisfactory if the fracture represents a more or less planar surface that parallels a crystallographic direction in a mineral. Cleavage is the fracturing of a mineral body along crystallographic planes, usually of low bond density, so that the observable break is a smooth planar surface. When plane surfaces are produced in a mineral by breakage along some such predetermined plane it is said to show parting (Hurlbut, 1959, p. 151). Parting, like cleavage, is related to planes of weak bonding, but, unlike cleavage, it does not necessarily take place parallel to atomic planes. Parting is related to weak planes arising from twinning, crystal imperfections (deformation lamellae, planes of liquid

inclusions, lineage structures), or crystal deformation. Fairbairn (1939, p. 352) defines parting as a rupture on the composition plane between two twinned portions of a crystal and cleavage as a structurally-controlled rupture that is independent of twinning. Cleavage is always consistent with the crystal symmetry and takes place only parallel to atomic planes. Although cleavage does not normally occur in quartz, a number of occurrences of cleavage in quartz have been reported.

Fairbairn (1939, p. 359-364) calculated the crystallographic planes in quartz that involved the least breaking of Si-O bonds. From these calculations he showed qualitatively that the best cleavage directions in order of decreasing facility should be parallel to r{$10\bar{1}1$}, z{$01\bar{1}1$}, m{$10\bar{1}0$}, c{0001}, a{$11\bar{2}0$}, s{$11\bar{2}1$} and x{$51\bar{6}1$}. Bloss and Gibbs (1963, p. 835-836) determined the number of Si-O bonds which would have to be broken per unit area for sets of rational planes in the (0001):($10\bar{1}0$) and (0001):($11\bar{2}0$) zones. Of the first set of planes r{$10\bar{1}1$} cuts the fewest bonds; in the second set ξ{$11\bar{2}2$} cuts the fewest bonds, with r cutting fewer than ξ.

Cleavage in quartz that has already been reported by other workers [Griggs and Bell (1938, p. 1738); Anderson (1945, p. 426); Borg and Maxwell (1956, p. 76); Bloss (1957, p. 227); and Bloss and Gibbs (1963, p. 837)] confirms Fairbairn's predictions. In the present work ruptures in quartz that have resulted from shock deformation and which parallel reported cleavage directions in quartz are, in order of decreasing abundance, r or z, c, m or a, and ξ. We refer to these crystallographically controlled ruptures as cleavages.

The nomenclature for quartz crystallographic planes used in this paper is:

r - the positive rhombohedron $\{10\bar{1}1\}$

z - the negative rhombohedron $\{01\bar{1}1\}$

m - the unit prism $\{10\bar{1}0\}$

a - the second order prism $\{11\bar{2}0\}$

c - the basal pinacoid $\{0001\}$

ξ - the second order trigonal pyramid $\{11\bar{2}2\}$

s - the second order trigonal dipyramid $\{11\bar{2}1\}$

x - the trigonal trapezohedron $\{51\bar{6}1\}$

Thin sections were studied on a 5-axis universal stage with a polarizing microscope. The orientation of the cleavage planes and the c axis of each grain were plotted on a stereonet and the angles between the c axis and the poles of the cleavage planes were then measured and used to determine crystallographic directions.

This method cannot distinguish between correlative forms such as $r\{10\bar{1}1\}$ and $z\{01\bar{1}1\}$ or $m\{10\bar{1}0\}$ and $a\{11\bar{2}0\}$. Thus, the symbol r is used to indicate the specific form and the correlative forms.

Meteor Crater Quartz

Meteor Crater, Arizona is 183 meters deep and 1220 meters in diameter and is encircled by a rim that rises 30 to 60 meters above the surrounding terrain. The exposed rocks in the crater range from Permian Coconino Sandstone to Triassic Moenkopi Formation in age. Beneath the raised rim lies a complex sequence of Quaternary alluvium and this unconformably overlies Moenkopi and Kaibab strata. The alluvium is composed,

in part, of material from underlying strata, meteorite fragments, and "fused rock" (Shoemaker, 1960, p. 420-421). Rogers (1930) described a "unique" occurrence of lechatelierite (silica glass) in the Meteor Crater sandstone. Chao, Shoemaker, and Madsen (1960, p. 220-222) reported the first natural occurrence of the high-pressure SiO_2 polymorph, coesite, from the sheared, partly fused, Coconino Sandstone of Meteor Crater. Because the existence of coesite indicates pressures in excess of 20 kbs., they suggested that the presence of coesite affords a criterion for the recognition of impact craters. Chao, and others (1961, p. 419-421) discovered the very high-pressure tetragonal SiO_2 polymorph, stishovite, in coesite-bearing rocks from Meteor Crater.

For the present investigation thin sections were made of the fractured, glassy, coesite-bearing Coconino Sandstone and of Coconino Sandstone that appeared to be unfractured and non-glassy in hand specimen. The former is extremely friable and has a sintered appearance. It is composed predominantly of quartz with minor amounts of silica glass, iron oxides, and coesite. No attempt was made to identify stishovite. The association of silica glass, coesite and quartz is shown in Pl. 1, fig. 1. The slightly deformed sandstone from the rim of the crater is gray-white and loosely cemented and is composed of quartz, iron oxides, and a trace of plagioclase.

Quartz grains in thin sections of the quartz-glass coesite material are highly fractured and are undisturbed with only limited development of cataclastic texture. Most of the fractures are planar and parallel to r or z, and less readily parallel to c, ξ, m or a and probably s. Cleavage in individual quartz grains can be seen in Pl. 2, figs. 1, 2, 3. Under crossed nicols extinction is extremely mottled. The extinction

pattern is unlike any observed by the writers in quartz from any other location with the exception of Wabar Crater. It is probably the result of microfracturing or slight plastic flow. Curved fractures are structurally controlled combinations of several cleavage planes. In Pl. 2, fig. 3 the dominant cleavages in the grain illustrated are r and c. The long curved fractures are combinations of r and c cleavages, predominantly, which form continuous curved fractures.

Quartz is slightly fractured and the extinction pattern is somewhat mottled in the undamaged sandstone but it is comparable to tectonically deformed quartz. The grains are subrounded and the majority are equant. In comparison some of the cleaved quartz in the deformed specimens has experienced a small change in shape. A few grains are elongated in the direction of the c axis and show cleavage parallel to the basal plane. Other changes in grain shape are caused by fragmentation around the grain exterior and by internal plastic flow after fracturing (Pl. 1, fig. 2). In general the change in grain shapes has not been extensive, nor is it a predominant feature in the majority of the grains studied. The subhedral quartz in Pl. 1, fig. 1 still retains several well developed crystal faces. The behavior of the cleaved quartz during deformation appears to have remained elastic until rupture occurred. In thin sections no evidence of shear faults have been observed; nor is there any apparent recrystallization of quartz.

Silica glass occurs interstitially between quartz grains. A few tongues of silica glass extend into disrupted quartz. The index of refraction for the silica glass, as determined by oil immersion methods is 1.468 ± 0.002. The silica glass presumably is formed from quartz by

shock induced "melting" (De Carli and Jamieson, 1959, p. 1675). The glass may have originated as a direct solid state transformation without actual melting.

Wabar Craters Quartz

The Wabar Craters near Al Hadida in east-central Arabia were discovered by Philby (1933). The largest crater occurs in a sandstone of undetermined age. The crater dimensions are approximately 92 meters in diameter and 12 meters deep. Glassy and cindery masses of material are strewn over the surface, and the walls of the crater appear to be built entirely of this material. Many fragments of meteoritic iron were found around the periphery of the crater. Spencer (1933) described various glasses, including lechatelierite, and shattered sandstone.

The Wabar sandstone is almost identical in mineral composition and textural appearance to the Coconino sandstone described above. The sandstone is composed almost entirely of quartz with interstitial silica glass, iron oxides and extremely small grains of coesite.

The quartz grains are anhedral to subhedral and are intensely shattered. Well developed cleavages, r, m and c, occur in practically all the grains with subordinate cleavage on ξ and possibly s appearing in a few grains. Most of the ruptures are cleavages; a few irrational fractures occur in most grains. Under crossed nicols the quartz grains exhibit mosaic extinction that may be attributed to rotation of cleaved segments and slight plastic flow. One grain is faulted parallel to r with offset of the intersected cleavage planes and slight plastic distortion of the material immediately bordering the fault surface.

Discussion

Meteor and Wabar craters were created by hypervelocity impact of large iron meteorites with the earth's surface. Stress resulting from this impact moved through the surrounding rocks in the form of a shock wave. Studies of shock effects from experimental deformation of solids under impulsive loading (Duvall, p. 52) show that at some sufficiently high value of shock pressure atomic bonds in a solid are not able to sustain the high stresses; the material either fractures or it yields plastically. In a simplified and idealized situation where a brittle solid is deformed under the effects of shock waves the material is first compressed to a higher density and then pulled apart. Chemical explosion experiments in rock show that the fracturing is the result of rock being pulled apart by tension waves (Duvall and Atchison, p. 1). It is well known that fracture occurs under rapid rates of loading. As an example, hot, semifluid glass, which normally deforms plastically may be broken by brittle fracturing if it receives a sudden impact.

Deformation of quartz specimens from Meteor and Wabar craters may be attributed to brittle fracturing along crystallographic planes and slight plastic flow after fracture. The fracturing of rock material by tension waves would favor extensive cleavage development in quartz. Cleavage is a tensile fracture that occurs normal to directions of minimum cohesion in a crystal. Initiation of a fracture along a cleavage direction probably originates at some pre-existing weakness or micro-crack where there is little or no cohesive strength and it is then pulled apart by tensile stresses.

The possibility of cleavage development by crack propagation and extension is illustrated in Pl. 1, fig. 1. In this case crack extension

(cleavage) has taken place along particular crystallographic planes; r, m and c. Cleavages along the rhombohedral crystallographic planes have been propagated from southeast to northwest in the photograph and terminate in the upper portion of the crystal. Corten and Park (1963, p. 29) state, in reference to fracture in MgO crystals, that less force is necessary to cause crack extension along certain crystallographic planes than to extend the crack along directions divergent to these planes. Thus cracks tend to follow these crystal planes and are not likely to branch along irrational crystal directions.

Christie, Heard and La Mori (1964) by experimental deformation of quartz attempted to produce plastic deformation by applying confining pressures equivalent to those at depths of 100 km. in the earth's crust. Their specimens failed by rupture along "faults" that were crystallographically oriented and they suggest that the faulting was initiated by small amounts of slip on planes parallel to c, r and z, and m and a. The experiments demonstrated that extensive plastic deformation of quartz does not occur under these conditions of high confining pressure (27 to 30 kilobars) and room temperature. They further suggest that the resultant textures might be similar to deformed quartz at meteorite impact sites. In recent experiments at high pressures (15-20 kb) and moderate temperatures (400-800° C) J. M. Christie and co-workers have produced fractures that developed parallel to deformation lamellae. The majority of the lamellae are parallel to c, r, z, ξ and ξ' (Christie, personal communication, March 1964). Quartz from meteorite craters studied in this investigation has failed by crystallographically controlled fracture. There is a lack of evidence suggesting extensive slip as the mechanism responsible for fracture development.

Cleavage fracture along with shear faulting and plastic deformation were reported from the Holleford Crater, Ontario, Canada (Bunch and Cohen, 1963). The quartz was described as being similar in textural appearance to experimentally deformed quartz. Future work involving the use of phase contrast microscopy and the electron microscope might resolve the question of whether slip or brittle fracture is the mechanism responsible for producing textures of the type discussed here.

The present work is a study of a few specimens and it is probable that quartz from various locations in a meteorite impact site that has sustained shock deformation over a range of pressures and temperatures would show the full spectrum of deformational behavior from brittle fracture to homogeneous plastic flow. A more extensive study of quartz-bearing rocks from these meteorite craters located as to exact depth and distance from the center of impact should yield a better understanding of the behavior of quartz under shock deformation.

The most striking feature of the shocked quartz is the apparently instantaneous brittle fracturing with very little movement of the shattered grains. The gross deformation of the quartz is notably different from quartz deformed by other processes; there is a definite lack of plastic deformation associated with fracture and extensive movement of grains or fragments. A significant development of cleavage in quartz may be a helpful criterion in recognizing structures created by meteorite impact or other shock mechanisms.

Acknowledgments

We thank Dr. R. C. Oftedahl, Dr. J. M. Christie, Dr. G. deVries Klein and Dr. W. H. Baur for critical review of the manuscript and A. M. Reid

for his assistance and helpful suggestions. Specimens were provided by E. P. Henderson of the U. S. National Museum and F. T. Lowrey of Pittsburgh, Pa. This work was supported by grants NsG-57-60, Supplement 1-62, and NsG-593 from the National Aeronautics and Space Administration.

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PLATE 1. QUARTZ FROM COCONINO SANDSTONE,
METEOR CRATER, ARIZONA.

Figure 1. Photomicrograph of a quartz grain showing crystal faces r, m and c with cleavages that are parallel to these faces. Coesite, iron oxide and silica glass are indicated at the periphery of the grain. C axis direction (arrow) and cleavages indicated in the photograph. Plane polarized light, x 80.

Figure 2. Photomicrograph of quartz illustrating cleavage parallel to the basal plane c and subsequent plastic flow. Crossed nicols, x 80.

PLATE 1

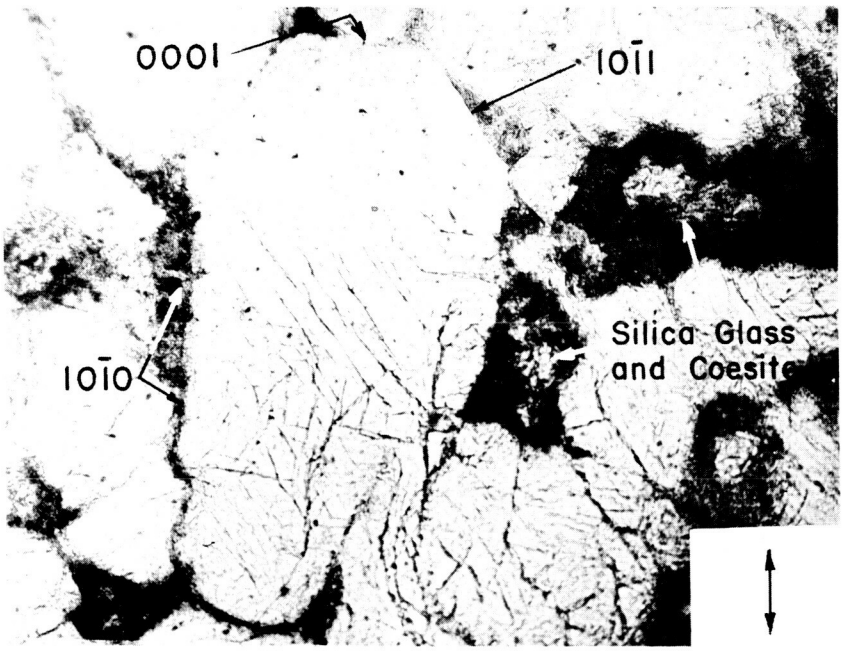

Figure 1

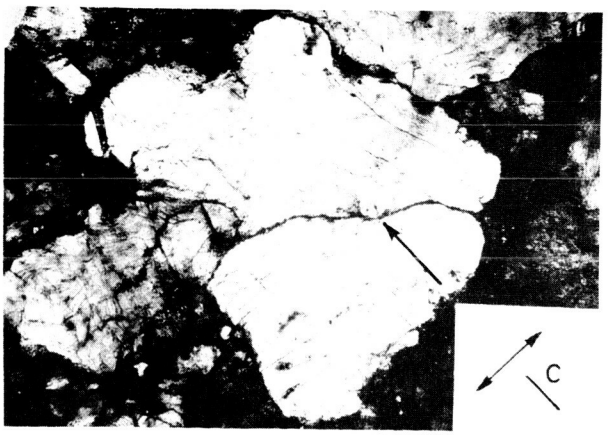

Figure 2

PLATE 2. QUARTZ FROM COCONINO SANDSTONE, METEOR CRATER, ARIZONA AND WABAR SANDSTONE, WABAR CRATERS, SAUDI ARABIA.

Figure 1. Photomicrograph (crossed nicols) of Coconino Sandstone quartz grain exhibiting r, r', m, and c cleavage. C axis direction (arrow) and cleavages indicated in insert box, x 150.

Figure 2. Photomicrograph (crossed nicols) of Wabar sandstone quartz grain exhibiting c, m and ξ cleavage, x 150.

Figure 3. Photomicrograph (plane polarized light) of Coconino Sandstone quartz grain showing combination of r and c cleavages which combine to appear as curved fractures, x 130.

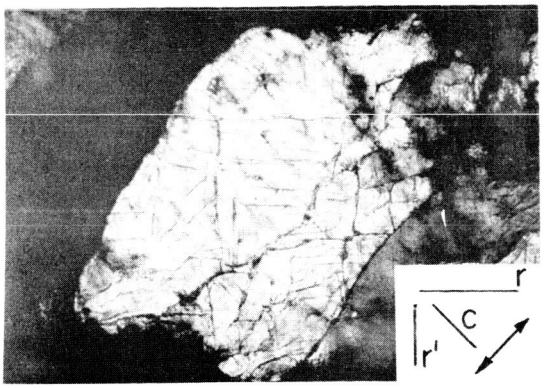

Figure 1

Figure 2

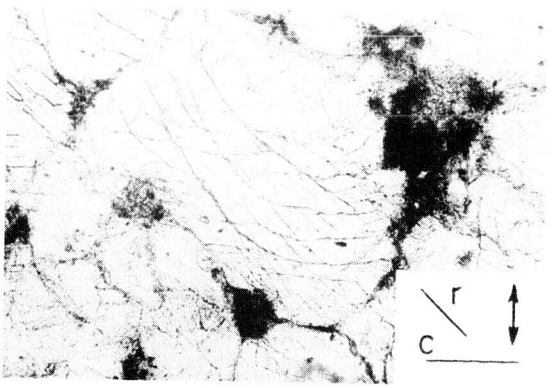

Figure 3